

Revitalizing the Space Shuttle's Thermal Protection System with Reverse Engineering and 3D Vision Technology

By Brad Wilson and Yishai Galatzer

Since the dawn of manned space flights, one crucial role of a spacecraft is to safeguard astronauts during the re-entry phase of space travel. The Space Shuttle's Thermal Protection System (TPS) provides a barrier to shield the Space Shuttle Orbiter from the intense heat of atmospheric re-entry, rising to a scorching temperature of 2,300°F (1260 °C).



Figure 1 – The space shuttle being transferred to launch site

The Shuttle is the only reusable space vehicle to ever make multiple flights into space. Due to its many missions, NASA needed an efficient method to fix and maintain the vehicle's heat shield. United Space Alliance, LLC is the NASA contractor in charge of this process.

Traditionally, the heat shield tile replacement process has been a time-consuming, manual endeavor. The search for a viable technique to fabricate the tile components started in the 1980's.

As 3D scanning technology improved and evolved, capturing the surface of each tile or cavity with a high precision scanner has become a viable method to support manufacturing the heat shield components.

TPS Processes Reviewed

After the Columbia accident, the revitalization process of the Thermal Protection System (TPS) underwent a critical review. As a result, the workload of the TPS team increased substantially, far beyond their capacity. The search for new technology, and a fresh methodology, was priority one for the department.

This time, the search proved to be fruitful. With the implementation of a fast, non-contact, white light scanning system, the TPS team has managed to save a significant amount of taxpayer dollars every year. The technology enables operation in demanding manufacturing environments, while overcoming vibrations, changing illumination conditions, and other problematic environmental factors.

The usage of the scanning system has steadily progressed into additional spin-off applications including reverse engineering, trouble-shooting, and

inspection. The system has also been reengineered to operate in hazardous environments.

The Challenges of Tile Replacement

In a nutshell, the TPS team faced formidable challenges. First, the heat shield for the Space Shuttle consists of over 24,300 individual thermal protection tiles. The tiles are made from silica, and the majority has a unique shape.

The procedure used to manufacture a thermal protection tile is elaborate and complex. But the end result is a tile with the precise combination of accurate fit, low weight, high strength, and the required thermal properties. The tiles are positioned literally all over the Shuttle, particularly on the lower surface enduring high air flow during the reentry process where extreme temperatures can melt the aluminum structure *See Figure 2.*

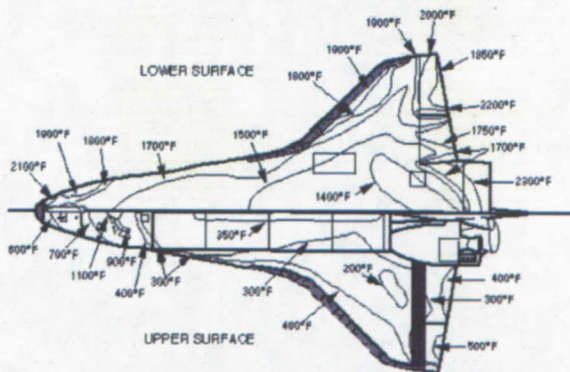


Figure 2 – Upper and lower surface temperatures

Prior to the Colombia accident, approximately 80 tiles were replaced per flight. The tile replacement operation was lengthy, painstaking, and complex.

One way to approach the problem was to make a pattern by hand to replicate the open tile cavity, and then copy the pattern into a silica-based tile using a gunstock machine. This method was inaccurate and at times required iterations to get close to the desired shape. *See Figures 3 and 4.*



Figure 3 – Hand made tile pattern

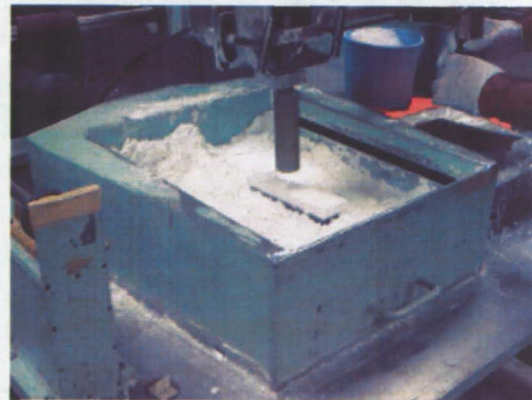


Figure 4 – Tile being cut on a gunstock machine

The alternative technique was based on the original tile designs. However, those did not represent the actual-as-assembled shape. The original designed tiles were reworked to fit. The original designs were not updated to represent these changes. Also the design tiles did not represent the changes from the stress

cycles experienced by the Shuttle Orbiter.

Hence, the replacement tile could not be produced directly from the original model. Instead the tile would be initially cut using a 5-axis milling machine, then trial fitted to the cavity. Once again, this procedure suffered from human errors, and several iterations were required to get the desired result. *See Figure 5.*

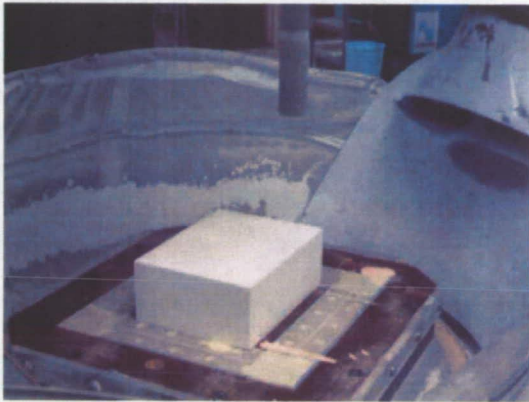


Figure 5 - Tile being cut on a 5 axis milling machine

New Standards Push Workload

When NASA launched its "Return to flight" program after the Columbia accident, a rigorous examination of the tile replacement operations resulted in the requirement to fabricate some of the tiles from a higher strength material. Other stringent controls were introduced for tile replacement.

These new standards resulted in a monumental increase in the workload of the TPS team. They now had to replace hundreds of tiles per flow. Although a large number of scanning products had been benchmarked for the job, the TPS team faced many obstacles. The following three limitations were the most significant.

First, the cavity that required measurement had a variety of color and reflectivity/shininess properties. The cavity could not be white sprayed, as the Shuttle is a space ready vehicle. The cavity created by the aluminum substrate, isolation materials, and neighboring tiles. These conditions pose problems for certain types of metrology devices. *See Figure 6.*



Figure 6 – Single tile cavity

Secondly, measurement and inspection had to be conducted on the actual spacecraft itself. All other activities would have to cease during the scanning process. Normally, 30 to 40 technicians work simultaneously around the clock to prepare the orbiter for its next mission. The technicians moving around generate a significant structural movement. Based on this drawback, the search was on for a solution that would not interrupt other critical work and delay the launch date.

Lastly, the Shuttle is covered by extensive scaffolding. There is simply no room, and no viable means to install an armlike measurement solution or other scanning devices in a stable manner to the scaffolding.

Solution Discovered

The engineering team led by Mr. Larry Nilsen and Steve Tyler identified a new

scanning technology. The device was based on a white light scanner with long-awaited features in the form of a flash-based light source, and fast double exposure capability. Using this 3D scanning technology, an entire scan area can be captured within less than 1 millisecond. Within this timeframe, the scanner captures markers and a slide projection. Due to the ultra short acquisition time, any vibration in the frequencies of up to hundreds of Hz would not affect the results.

The white light scanner uses three synchronized cameras to view a prescribed pattern and applies a point cloud to a surface. The same system can also use a 2D image from the cameras to determine the position and size of a variety of surface features such as holes, slots, edges, and more.

The TPS team asked for a demonstration at the Orbiter Processing Facility (OPF). CogniTens, Inc. presented the Optigo 200 system (see Figure 7) at the Kennedy Space Center. During the evaluation period, tile cavities were scanned directly on the shuttle. The scanning was performed while other technicians continued to work all over the shuttle. The point cloud was then processed into an STL file using the wrap functionality of Geomagic Studio, software from Geomagic, Inc.

Next, the TPS team assessed the accuracy and repeatability of the system. The evaluation took place utilizing a TPS technician as the scanning system operator. The data reference was a DEA CMM machine. The accuracy and repeatability results were verified, and the Optigo was approved to be part of the USA standard process.



Figure 7 – Optigo 200 system

New Tile Replacement Process is Born

The next order of business was to devise a viable methodology to reverse engineer the tiles and cavities. CogniTens, United Space Alliance, LLC and Ogihara America Corporation formed a team to test and map out the entire process. Ogihara America Corporation is a Tier-1 supplier to the auto industry around the world. Coming from the stamping die engineering world, Ogihara's specialized skills proved to be advantageous in implementing a real world reverse engineering procedure.

The new procedure involved scanning the cavity, converting the point cloud into an STL file, and importing the data into a CATIA CAD system. The CAD operator then created offset surfaces from the adjacent tile walls to generate a new CAD design for the tile. This CAD model served as the new master file, and the data source for the CNC program.

The first trial run was achieved in only 5 hours, from scanning to a completely machined foam pattern. This was a

dramatic improvement as compared to the normal benchmark of up to one week per tile. *See Figures 8 through 11.*

The routine was then standardized, and today is an approved method for tile replacement. The process was later expanded to produce several tiles at the same time, in situations where multiple tiles had to be removed in a specific area. *See Figure 12.*

team looked to further expand the scanner's application base.

The Benefits Accumulate

The advantages of the implementation were clearly recognized in the following areas:

- Reduced tile scrap rate
- Diminished rework rate
- Improved quality
- Faster process cycle time
- And a significant decline in the

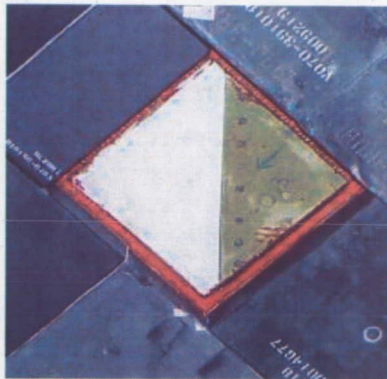


Figure 8 – tile cavity



Figure 9 – point cloud



Figure 10 – test pattern in place



Figure 11 – test pattern fully assembled

Another important landmark was achieved, the first 41 tiles created using the new techniques required no iterations at all! This progress alone translated into significant time savings and greater productivity in the tile replacement endeavor. Inspired by the success, the

use of rare and toxic materials

This new method was studied closely by NASA and the Astronauts of the STS-114 mission. Demonstrations and basic training were conducted before the launch. *See Figure 13.*

Due to the new strength requirements, tiles located around openings such as the landing gear doors had to be changed in bulk. In order to tackle this application, a virtual assembly technique was implemented.

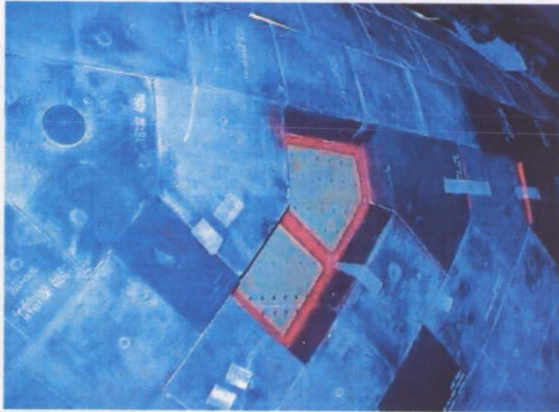


Figure 12 – Cavity left by removing two adjacent tiles

Conventionally, this process would still take many weeks to execute while keeping the doors closed. This intrusion would obviously slow down other tasks taking place on the shuttle. The team was ready to try a new approach.

The TPS team scanned the doors in open and closed positions (*see Figure 14*). They removed the tiles to be replaced, and scanned the resultant cavities. Using digital assembly tools in the CogniTens software, all the measurements were assembled into one point cloud. The team proceeded to design new tiles to fit into the open cavities. The end result was successful and introduced notable timesavings to the overall OPF activity. *See Figure 14.*

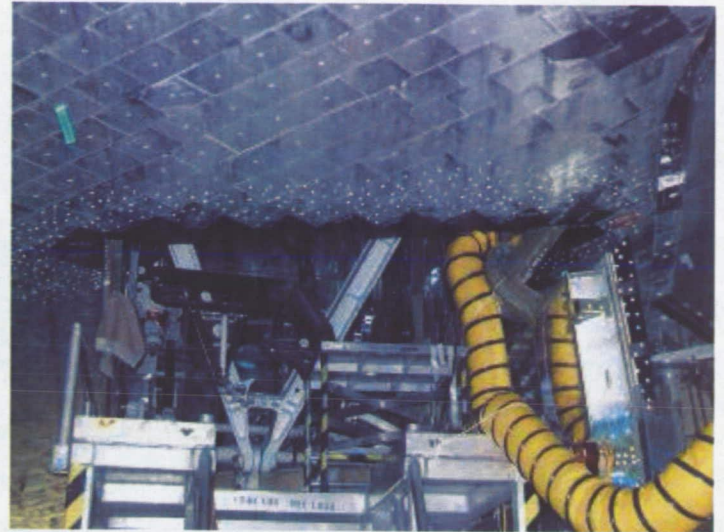


Figure 13 – Landing gear door in open position

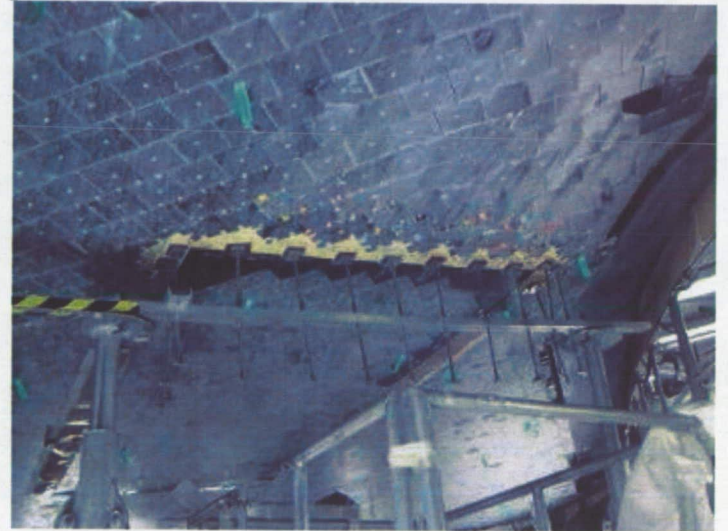


Figure 14 – Landing gear door in closed position, showing mockups being fitted.

One More Hurdle to Cross

Two more Optigo systems headed to the remaining two Orbiter Processing Facilities, but found a serious roadblock awaiting them. The Kennedy Space Center had implemented new fire safety codes and regulations. Every new piece of equipment used in the OPF had to comply with NFPA Class I Div II explosion-proof requirements.

These restrictions led to the development of a new Optigo system that can be operated next to the shuttle containing Monomethyl Hydrazine (MMH), and Nitrogen Tetroxide (N₂O₄). The scanner employs pressurized enclosures and explosion proof controls that meet all the relevant safety requirements. Both systems are fully operational in the Orbiter Processing Facilities today.

Spin-off Applications and Beyond

Scanning technology has also proved effective for developing protective covers for critical components. The main engine nozzles of the Shuttle were scanned. Utilizing the point cloud data, molds were created to produce protective covers that shield the nozzles from launch site related debris. See *Figures 15 through 18.*

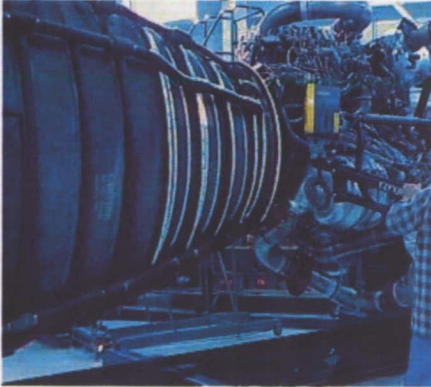


Figure 15 - Main engine nozzle being scanned

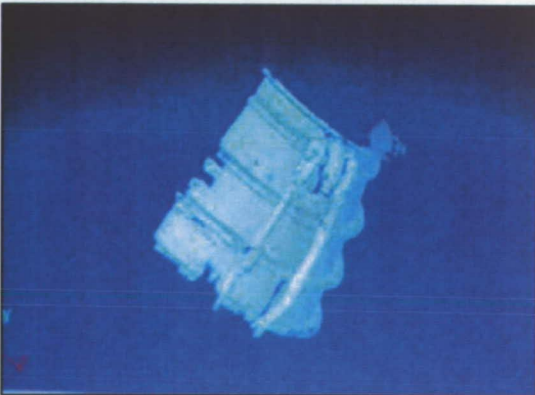


Figure 16 - Point cloud



Figure 17- Protective covers being tried out

Another use of the scanner is for post flight debris damage assessment. During the first few days of a mission, Shuttle areas sustaining damage are scanned, and then analyzed to see if a fix is required.

After the Shuttle landing, surface damage was gathered with the scanner to verify in-orbit assessments and compare the data to post re-entry characteristics. This information was also used to investigate the source and the impactor. See *Figure 18 and 19.*

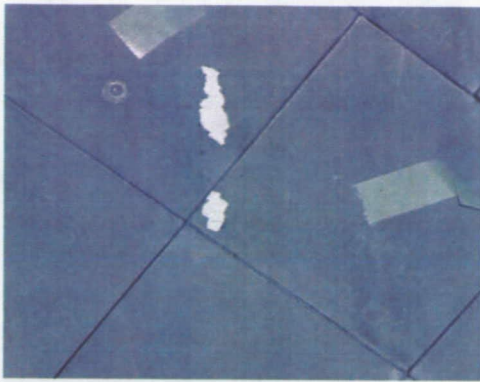


Figure 18– Post flight damage



Figure 19 – Post flight damage scan

Summary

The white light scanning system has been implemented in the Shuttle operations, and proven to be a major engineering achievement for the TPS group. The team not only achieved lean 6-sigma objectives in the form of cost savings, but also met 100% of their goals in regard to replacing tile cavities. The team also initiated additional uses of the scanner to other areas of shuttle maintenance. Faced with the retirement of the Shuttle fleet in a few short years, the TPS team is in good shape to confront new applications and challenges with a proven track record to tackle all in their path.

Acknowledgements

United Space Alliance, LLC ("USA") is a Delaware limited liability company equally owned by The Boeing Company and Lockheed Martin Corporation. USA is NASA's primary contractor in human space operations, including the Space Shuttle and the International Space Station.

CogniTens, Inc. is owned by Hexagon Metrology, and its US headquarters is located in Wixom MI. The company's sales and support centers are located in Nashville, TN; Seattle, WA; Lake Forest, CA; and St. Louis, MO.

CogniTens sells and supports the white light Optigo system, and the automated OptiCell system. CogniTens specializes in process development with its customers to ensure successful end-to-end implementations

Ogihara America Corporation is a worldwide supplier of high-end stamping dies and assembly tooling for auto closure systems and body sub- assemblies. Since 2000, Ogihara has been researching and implementing scanning technology in their engineering and manufacturing operations. The company serves as an industry benchmark for successful implementations.

Geomagic, Inc. is a global software and services company headquartered in Research Triangle Park, North Carolina, with subsidiaries in Europe and Asia. Geomagic Studio Wrap and Shape modules are used in the reverse engineering process.



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Brad Wilson - United Space Alliance, LLC Yishai Galatzer, CogniTens, Inc.

CogniTens



Post Columbia Challenges

- Replacing Silica heat protection tile in between flights was always a challenge
- New requirements post the Columbia accident, stretched the existing processes past their limits
- A revolutionary scanning technology addressed the challenges and implemented successfully



Limitations of Traditional Tile Fabrication Process

- Most tiles have a unique design
- Tolerance build up from surrounding tiles creates a unique cavity
- Tolerance build up is not reflected in our theoretical CAD data.
- Established processes involved a significant amount of iterations, before being able to cut a final tile

This resulted in a high cost per tile, and a long turn around time



Traditional Process Methods

A foam pattern is made by hand.

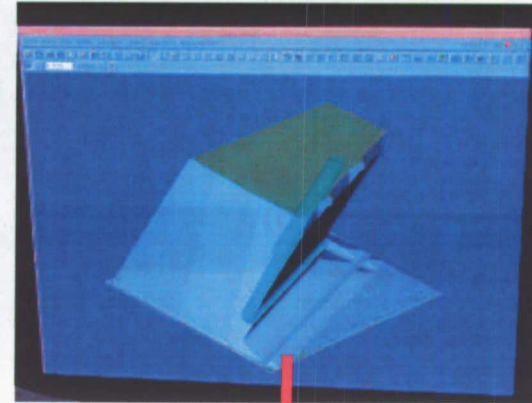


Pattern Is then traced with a gunstock machine

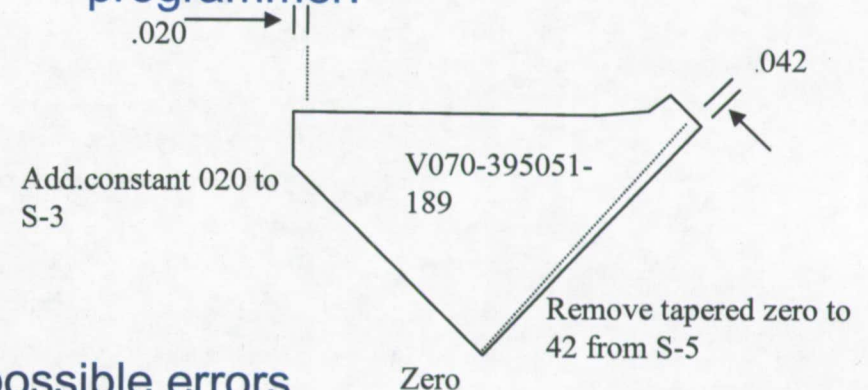


Several iterations, with many points of possible errors

NC pattern cut from theoretical data.



A sketch is then made with the required alterations for the programmer.



Our Challenges

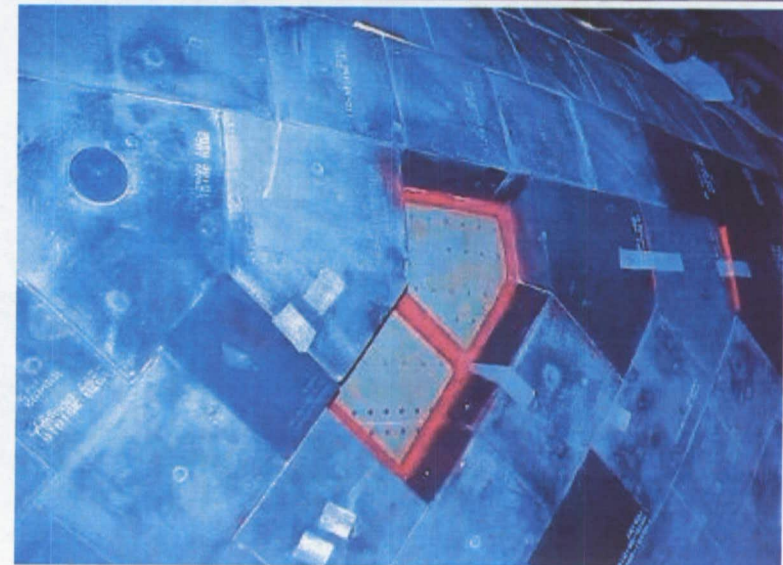
- Pre Columbia accident involved replacing about 80 tiles per normal processing flow
- Post Columbia the criteria for damage requiring replacement was tightened resulting in increased tile replacement
- Columbia investigation team recommended strengthening the tiles at certain areas of the orbiter further increasing workload
- The post Columbia replacement rate was now at hundreds of tiles per flow

Equipment Evaluation Phase

- Due to the nature of the objects measured, white coating was strictly prohibited
- Structural vibration of the orbiter was a key limiting factor for other pieces of equipment evaluated
- Steve Tyler one of our TPS engineers, identified a new type of white light scanner
- Demonstration was scheduled, and scanning of the cavities was done successfully on the actual orbiter

Key Technical Challenges

- Extensive scaffolding around the shuttle, no solid attachment point for equipment
- 30 to 40 technicians are working at a time on the shuttle, leading to structural vibrations
- Large variety of colors and finishes possible in the cavity and surrounding tiles
- The new tool proved to overcome all of these



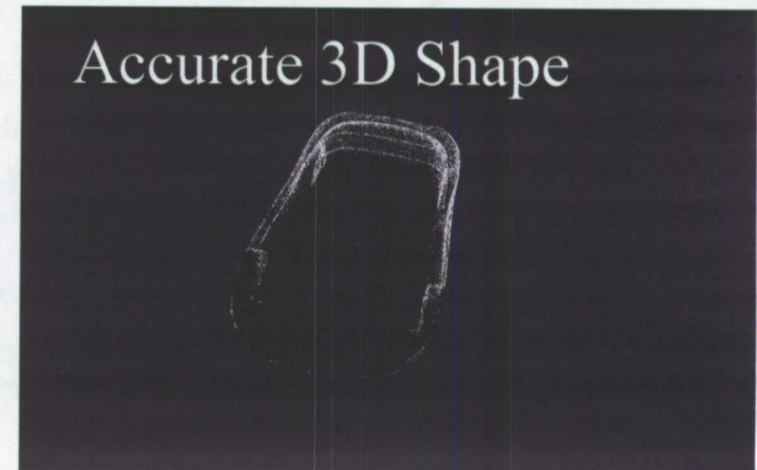
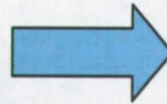
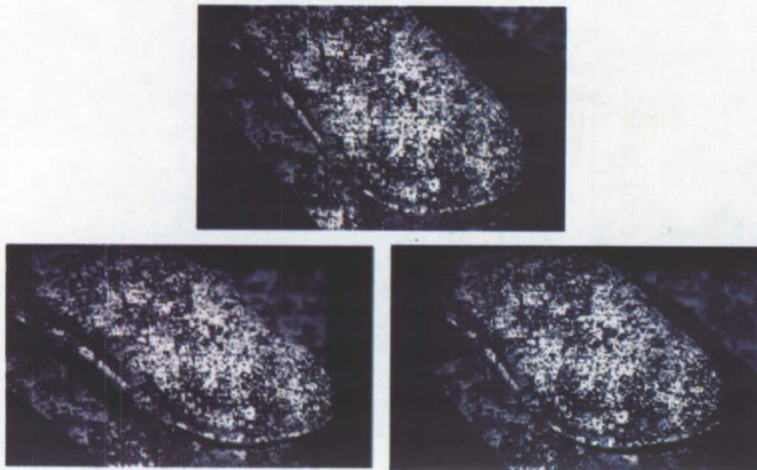
Equipment Selected

- USA select the Optigo 200 system, since it met the above challenges
- The system implements a unique white light technology



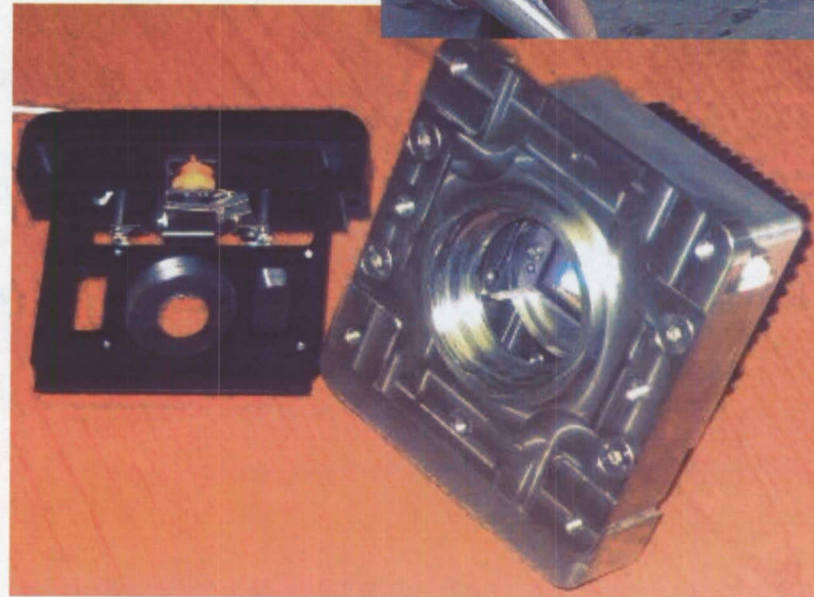
Enabling Technology

- **Reconstruction from one image projection**
- **Flash based light source**
- **Less than 1 millisecond exposure time**
- **This short time enables reconstruction of an area while it's moving relative to the optical head, and also allows for low sensitivity to external light sources**



Enabling Technology

- Dual shutter cameras, enabling two sets of images acquired micro seconds apart
- The two images with two different light sources were acquired within less than 1 millisecond
- One shot captures retro reflective targets while the other captures the surface
- This enables motion of the optical head and the object during the image acquisition and thus handheld operation in a vibrating environment

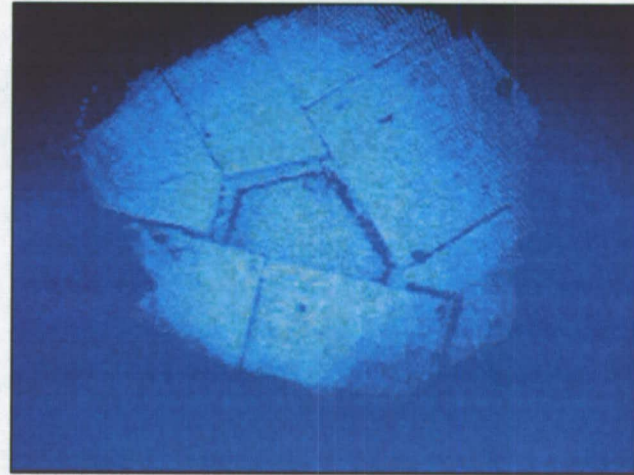


Team Building

- An expert team implemented the new process
 - TPS Engineering
 - CAD Engineering
 - CogniTens, Inc
 - Ogihara America Corporation
- First trial completed in 5 hours, compared to up to a week

New Process

- The process involved scanning the cavity on the orbiter
- Reverse engineering the cavity to create tile design to fit the as built condition
- 5 axis mill cut the new tile
- Fit and assemble



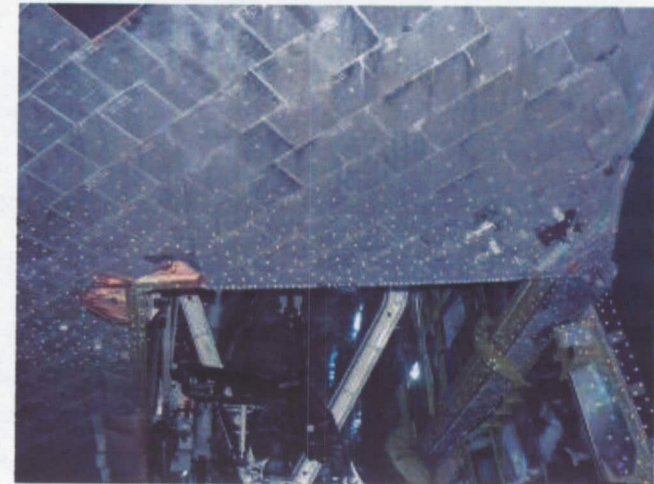
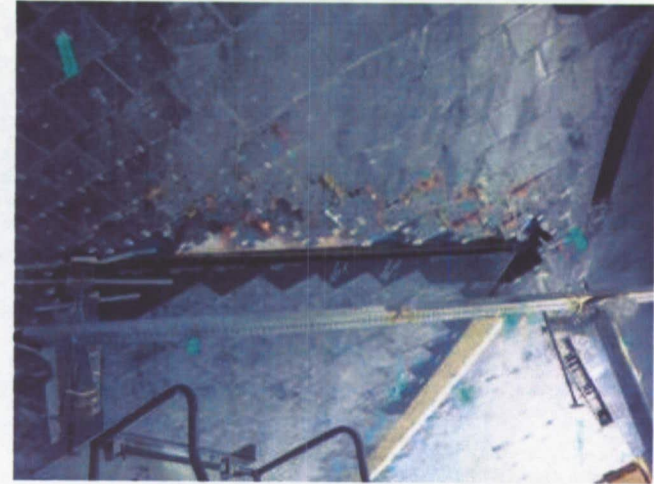
Return to Flight – STS 114 Mission

- The STS 114 mission fully utilized the new technology
- Estimated cost savings cannot be disclosed but the implementation more than paid for itself
- The astronaut team reviewed the technology and its implementation
- Mission accomplished!



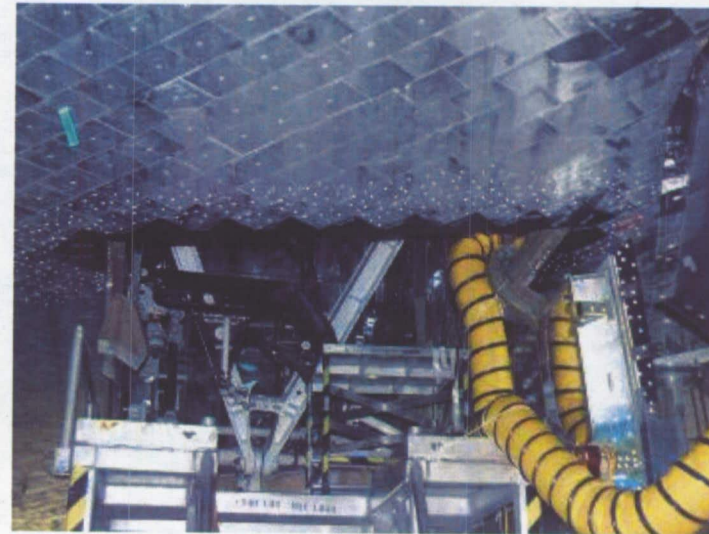
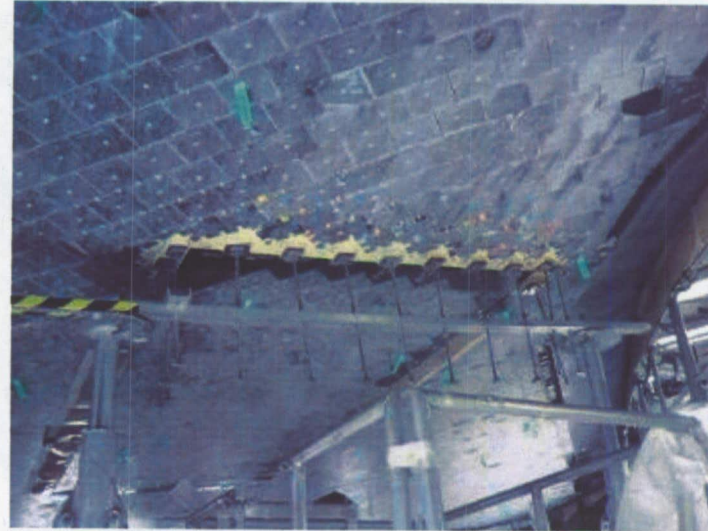
Tackling the Large Mods

- Large sections had to be replaced to a higher strength material
- Mostly around openings
- Scan the door in an open position with tiles installed
- Tiles removed and a second scan is performed
- The door is then closed and a third scan is done



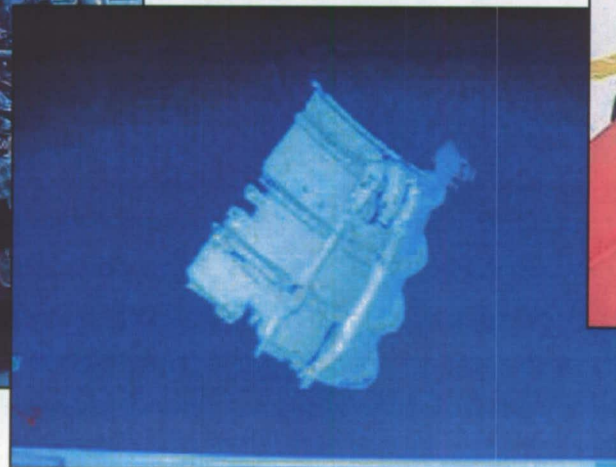
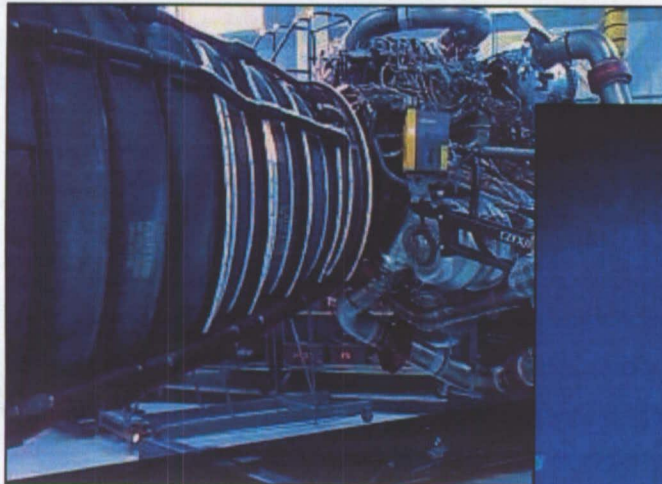
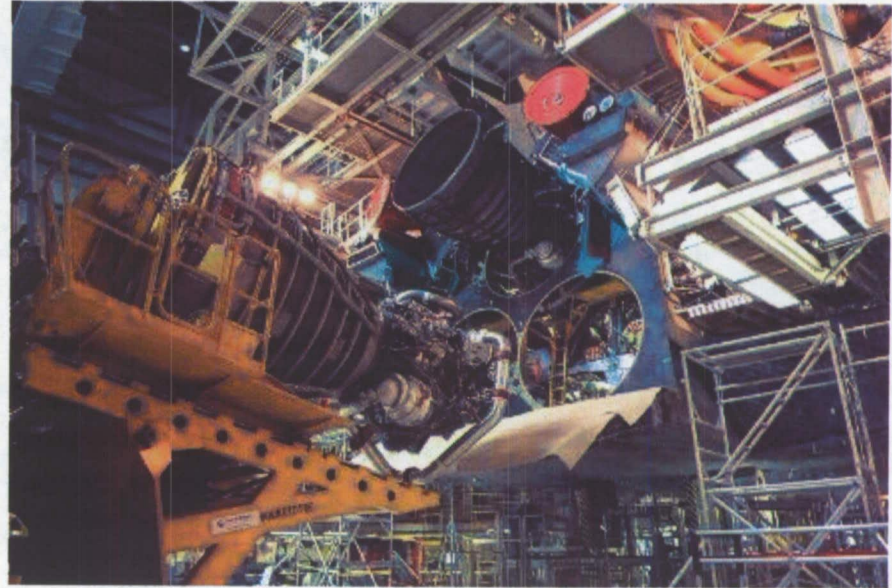
Tackling the large mods

- Scans digitally assembled in closed position, resulting in exact cavity details
- Our old methods of hand fabrication or NC would require the doors to be closed for weeks!
- Time of doors closed was minimized, major enhancement for the rest of the systems workflow



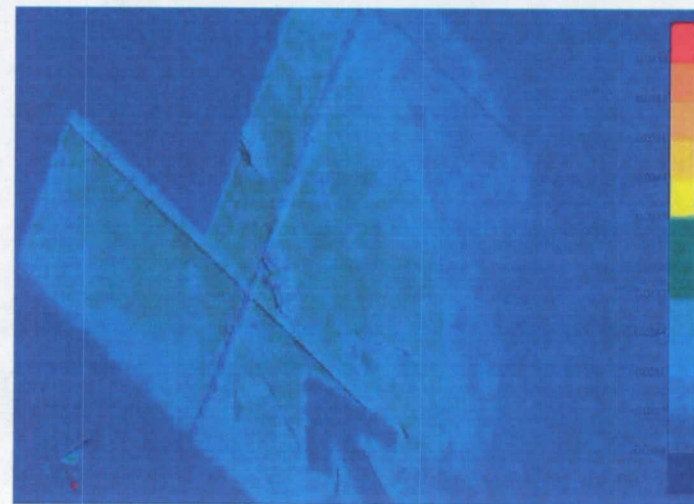
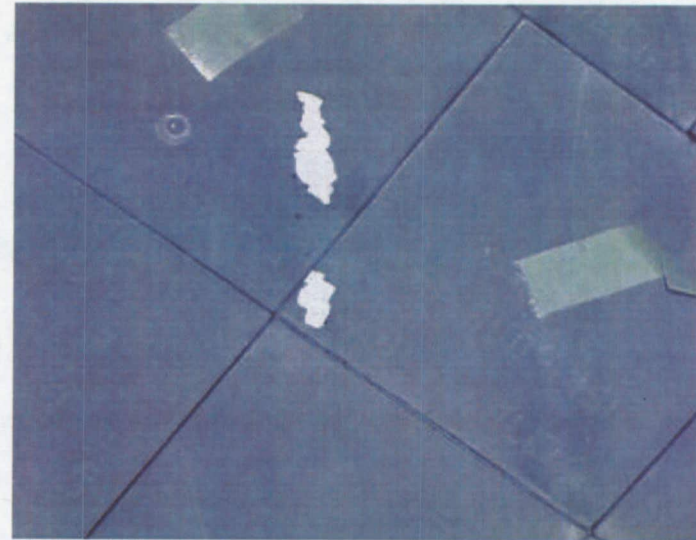
Additional Applications at NASA

- Scanning critical components for mold making of protective covers



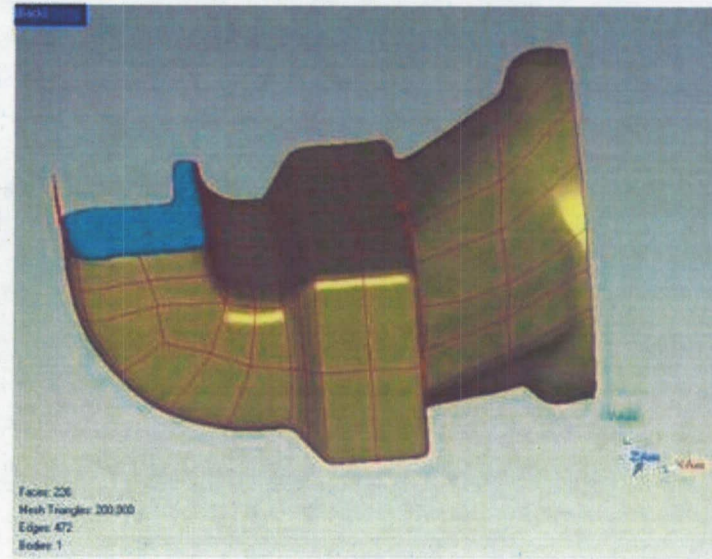
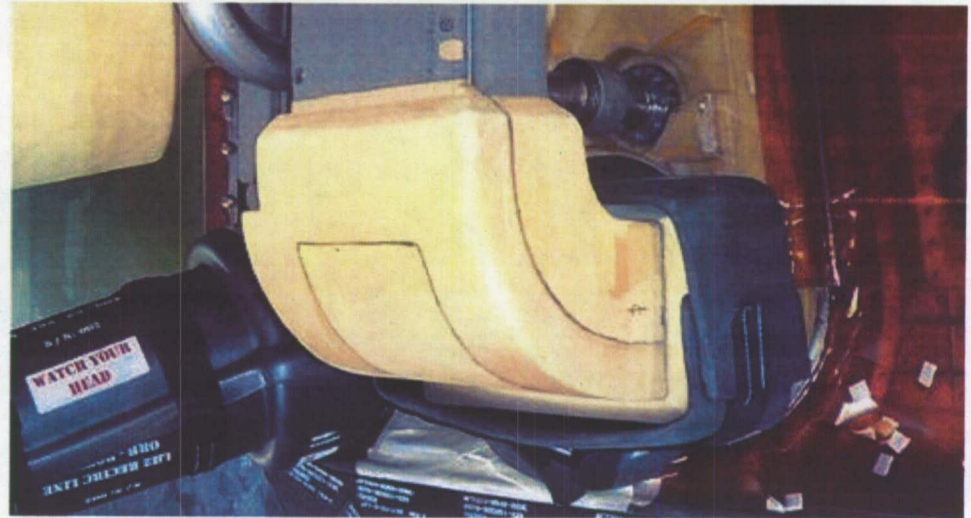
Post Flight Debris Damage

- Scanned post flight debris damage
- Date used for comparison between on-Orbit and post reentry differences
- Cavity characterized to determine the potential impactor



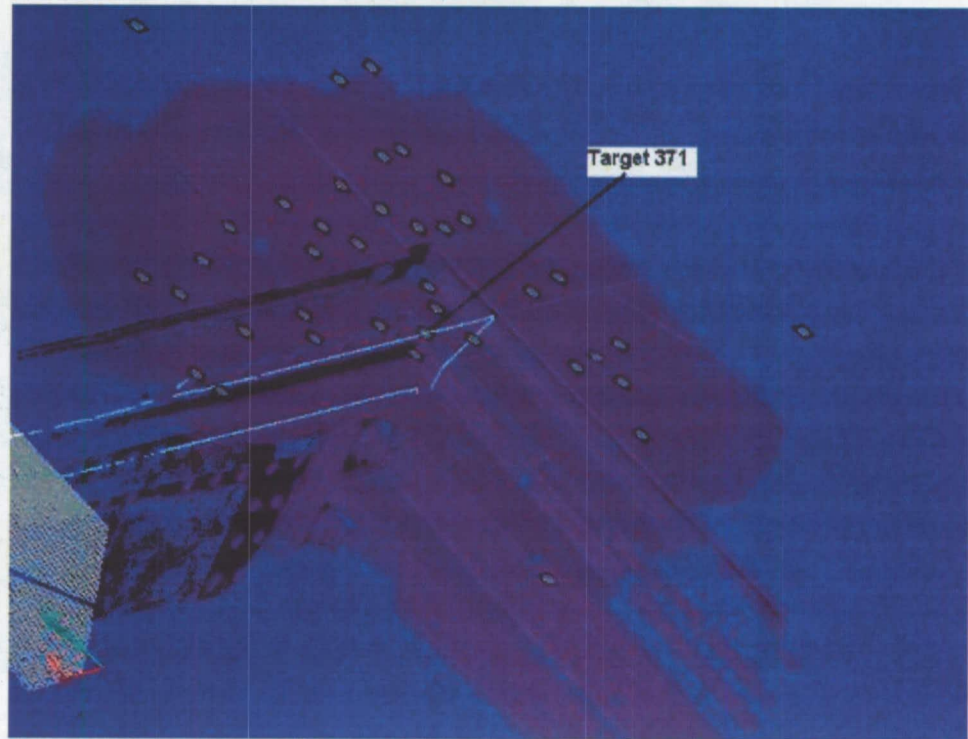
Further activities

- **In Flight Anomaly**
- Used the system to aid in the analysis of a protruding sleeving material that may have caused early transition that caused an increase in temperature to the lower surface during reentry of STS 116.
- **Trouble Shooting**
- Used the Optigo to assist in identifying various discrepancies in ground support components.



Main Landing Gear Door Measurement Evaluation

- This was a program level design evaluation to study the stress loads on the doors during launch and reentry.
- We used the system to scan the door to structure interface and transfer the scan data into the Shuttle Orbiter coordinate system, we then provided our design engineering team with “as built” CAD data to directly compare to the design CAD data.



Little Bit About Us

- United Space Alliance, LLC ("USA") is a Delaware limited liability company equally owned by The Boeing Company and Lockheed Martin Corporation. USA is NASA's primary contractor in human space operations, including the Space Shuttle and the International Space Station.
- **CogniTens** – 3D Scanning White Light manufacturer, part of the **Hexagon group**. CogniTens is the maker of the Optigo and OptiCell white light systems



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